INFLUENCE OF PASSENGERS DURING COACH ROLLOVER

James Anderson
Majid Sadeghi
Cranfield Impact Centre Ltd.
UK
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ABSTRACT

UN-ECE Regulation 66 [1] provides rollover safety for coach passengers by ensuring an adequate residual space remains during a standard rollover test. At present the energy requirement of the coach superstructure depends directly upon the unladen mass of the vehicle, with the passenger mass assumed to be self-arresting.

However, all modern coaches possess either 2 or 3-point seatbelts and if used by the passengers, the extra mass coupled to the coach structure increases the amount of energy to be absorbed during the rollover test.

Within the EC and DfT(UK) funded ECBOS (Enhanced Coach and Bus Occupant Safety) project, bay section rollover testing and validated computer simulations were performed in order to quantify the influence of the passenger mass on the structural deformation during rollover.

This work found that the percentage mass of the occupant that is effectively coupled to the coach structure during rollover was 71% for lap-belts, 93% for 3-point belts and 18% for unrestrained. These results will now be used for possible modernisation and updating of the Regulation.

INTRODUCTION

The UN-ECE Regulation 66 (R66) rollover test involves 'gently' rolling a coach or bay section of a coach into a 800mm rigid ditch (Figure 1). The structure is slowly tilted on a platform, until it's centre of gravity causes it to topple under it's own weight into the ditch. The criteria for passing the test is that no intrusion into the passenger residual space occurs (Figure 2).
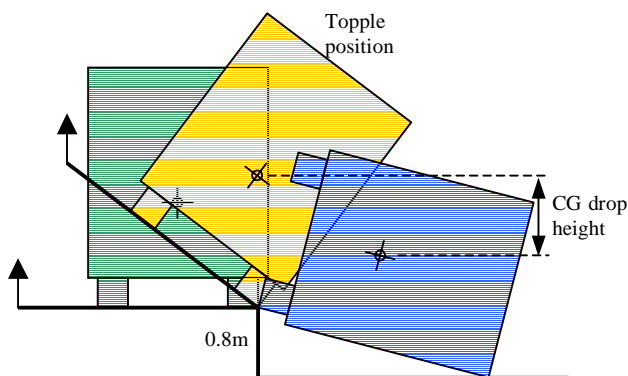

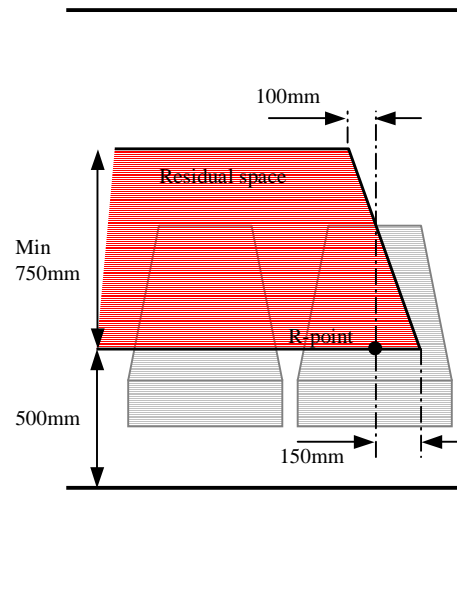**Figure 1. Phases of R66 rollover test.**

Figure 2. R66 residual space template.

The regulation may also be passed by assessing the energy absorption using a numerical model that includes component test data (calculation method).

The current regulation requires the coach structure to be unladen when tested (ie. no passengers or luggage). However, with seat belts becoming more common in coaches, the restrained passengers will increase the effective vehicle mass and also it's centre of gravity height. This would increase the deformation of the vehicle during a rollover accident and hence increase the risk of injury to the passengers.

Therefore updating of the regulation is required in order to take account of the potential passenger mass that may be coupled to the coach during rollover. Due to the fact that passengers are not rigidly attached to their seats when belted (ie. certain body parts are still free to move), it is necessary to find what proportion of the passenger mass is *effectively coupled* to the seat. This will vary for 2 and 3-point seat belts, as different body parts are being restrained by the two belt types.

This study has quantified the proportion of the passenger mass that is coupled to the coach for 2 and 3-point seat belts and also for unrestrained occupants.

It is envisaged that the R66 rollover regulation will, in future, take account of the increased loading as follows:-

- Full vehicle/bay section rollover test will carry an appropriate ballast rigidly tied to the structure.

- Calculation method for passing R66 will increase the energy absorption requirement (E*) by an appropriate factor.

ROLLOVER TESTING OF BAY SECTIONS

Two bay section rollover tests were performed in order to assess the influence of lap-belted occupants and provide validation data for the computer models.. The two tests used identical bay section structures, the first without any dummies and the second with four 50%ile Hybrid III lap-belted dummies.

Bay section design

The general design of the bay section was taken from an R66 approved TransBus [2] coach design constructed from mild steel. The TransBus coach was designed for the R66 energy to be absorbed by seven similar body rings along it's length, requiring each ring to absorb approximately 9kJ of strain energy before contact with the R66 residual space template.

The basic bay section design (Figure 3) used two complete body rings (ie. one ring consists of 2 window pillars, roof cross beam, floor cross beams attaching through to chassis longitudinals). These two rings were connected via longitudinal beams at floor, waist and roof level. A stiff framework connected the rings below the floor level and helped to provide a stable structure.

Figure 3. Basic bay section frame.

Each bay section had one row of seats (Figure 4) with retractable arm-rests. Each individual seating position was fitted with a lap belt.

Each bay section was fitted with a 1mm sheet steel roof panel and 1mm sheet steel window panel on it's ground contact side. These panels were included to allow the dummies to interact with the bay section in a realistic manner.

Figure 4. Bay section with welded strip masses (grey), bolted lumped masses (red) and seats.

Mass and CG Height Determination

Extra mass was required to ballast the bay section so that during the rollover it's predicted deformation would be close to the R66 residual space and provide permanent structural deformation.

From component testing performed during a previous project on the same structure, it was estimated that the two body rings in the bay section would absorb approximately **18** kJ before contact with the R66 residual space.

The ballast was obtained by a combination of permanently welded steel strips (grey) and bolted steel blocks (red) at floor level (see Figure 4). The bolted blocks could be transferred between the bay sections, reducing the amount of ballast required for the two rollover tests.

The main design parameters of the bay section were then as follows:-

Height (H)	3.50	m
Width (W)	2.46	m
Length	1.80	m
CG Height (H_s)	1.65	m
Total Mass (M)	1,920	kg
Framework + panels	*362*	*kg*
Welded strips (grey)	*538*	*kg*
Bolted blocks (red)	*937*	*kg*
Seats (2 pairs)	*83*	*kg*

From the above data and using the E* equation from [1] to calculate the total energy absorbed by the structure during rollover,

$$E^* = 0.75 \, M \, g \left[\sqrt{\left(\frac{W}{2}\right)^2 + H_s^2} - \frac{W}{2H}\sqrt{H^2 - 0.8^2} + \frac{0.8 H_s}{H} \right] \quad (1)$$

E* = 0.75 x 1,920 x 9.8 x 1.24

E* = **17.5** kJ (estimated energy to be absorbed by the bay section during rollover)

Test Instrumentation

The following instrumentation was used during each rollover test:-

- Four wire potentiometers were used to record the time dependant displacement of the two window pillars on the contacted side, at cant-rail and waist-rail levels (see Figure 5).

- One off-board high speed digital camera was positioned to view the front of the bay section.

- Two off-board normal speed VHS cameras were positioned for a general view and rear view of the bay section.

Figure 5. Two wire potentiometers attached to the front body ring.

**Rollover Test Results**

  Rollover Test 1: No Dummies

Figure 6. Rollover test 1: Permanent deformation of bay section.

No material separation occurred during the rollover test. The main plastic deformation was due to bending in the window pillars at floor and roof level

The maximum displacement at the top of the window pillar was 414mm, the permanent displacement was 340mm. The displacement time histories of the four wire potentiometers are shown in Figure A1 in the **Appendix**.

  Rollover Test 2: Four Lap-belted Dummies

Figure 7. Rollover test 2: Permanent deformation of bay section.

No material separation occurred during the rollover test. The main plastic deformation was similar to that in rollover test 1 ie. bending in the window pillars at floor and roof level. The four dummies remained securely belted throughout the rollover test.

The maximum displacement at the top of the window pillar was 467mm, the permanent displacement was 380mm. The displacement time histories of the four wire potentiometers are shown in Figure A2 in the **Appendix**.

  Comparison of Deformation

The inclusion of lap-belted dummies caused the bay section to deform an extra 53mm at the top of the window pillar. A visual comparison of the maximum elastic deformation for each bay section is shown in Figure 8.

Rollover Test 1   Rollover Test 2
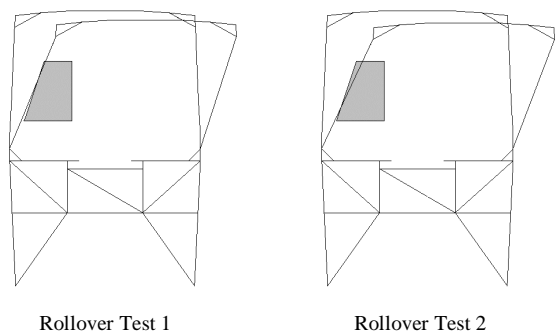
Figure 8. Sketches of bay sections showing maximum elastic deformation.

COMPUTER SIMULATIONS

General Model Description

The principle of the computer model was to simulate the dynamic rollover tests of the coach bay section structure including dummies. Once the computer model had been validated using the test data, it would then be used to gain additional information on the rollovers (eg. energy values) and also to predict the effect of varying further parameters (3-point belted and unrestrained dummies).

The computer model (see Figure 9) was created as a three dimensional finite element model and run using the explicit LS-Dyna3D software. The geometry of the model was the same as the bay sections used during testing.
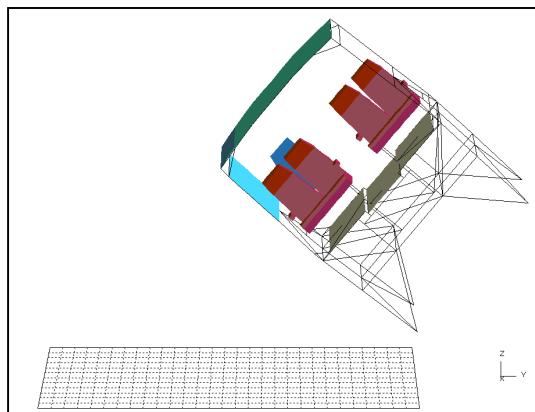
Figure 9. FE model of bay section.

The simulation began from the point of topple of the bay section, allowing it's free fall motion to be modelled and the speed upon impact with the ground to be automatically calculated.

During the free fall motion of the bay section, the base of the two legs were constrained artificially. The constraints only allowed rotation about the longitudinal axis of the bay section and at the point of impact with the ground, were released allowing the bay section to move freely.

The ground was modelled as rigid and non-failing.

The steel tubular framework of the bay section was modelled using 3D beam elements. These allowed moment versus rotation properties to be input directly to the likely hinge locations providing accurate elasto-plastic collapse behaviour. Otherwise the beams deformed elastically according to their theoretical properties.

The roof and window panels were modelled using 3D shell elements and rigidly attached to the beams (ie. no detachment allowed). The shell elements possessed theoretical elasto-plastic material properties.

The seat geometry was taken directly from the actual seats used during the rollover tests. The seats were modelled mainly using rigid solid elements in order to reduce the CPU run time. The part of the seat back that deformed during testing was modelled using deformable elements, with theoretical material properties. All the seat elements allowed a friction coefficient to be defined between themselves and the dummies.

Each seat under-frame was simplified by the model and only allowed rotation to occur at three points (seat joint to sidewall, top of legs, bottom of legs). The rotational stiffness at these points was arbitrary and was one of the properties varied during the model validation process.

Standard FE Hybrid III 50%ile dummy models (from LS-Dyna3D) were used to represent each of the four dummies (see Figure 10). Each dummy consisted of 3D shell elements that represented the outer surface of the dummy volume. The joints between the body segments used the validated stiffness properties supplied with the model.
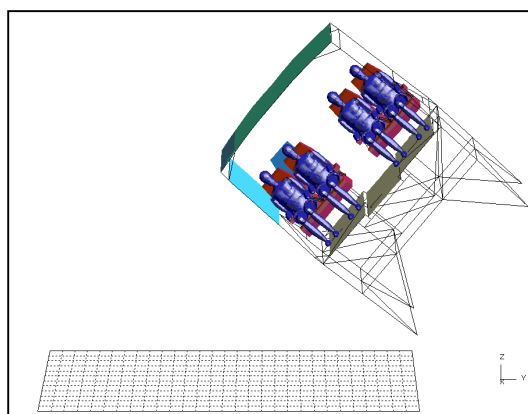
Figure 10. FE model of bay section including four Hybrid III 50%ile dummies.

Bay Section Model with No Dummies (bay_sim1)

The '*bay_sim1*' model consisted of the following attributes:-

Nodes:	1,630
Beam elements:	261
Shell elements:	176
Solid elements:	560
Lumped masses:	58
Spring elements:	4
Joint elements:	14
Seatbelt elements	0

The model was calibrated to match the same maximum displacement at the top of the window pillar that was recorded during rollover test 1 (ie. 414mm). In order to achieve the correct displacement, the following parameters were varied:-

- Elastic stiffness of seat leg joints

- Moment versus rotation data for bottom of sidewall stump pillar and diagonals

The following time history graphs for '*bay_sim1*' are shown in the **Appendix**:-

- Figure A3 - displacement time histories at waist level and top of window pillar
- Figure A4 - comparison of FE displacement data with the test data from rollover test 1
- Figure A5 - energy time history graph (kinetic energy and internal energy)

Figures 11 and 12 show the model at the point of maximum deformation and permanent deformation respectively.
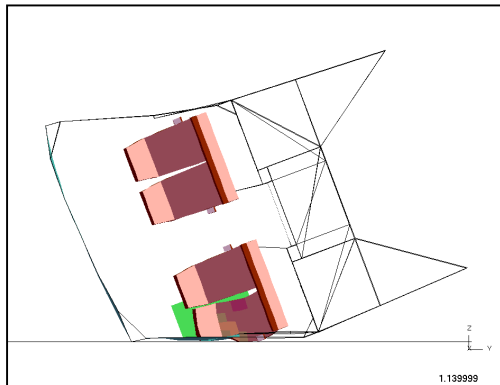
Figure 11. Model '*bay_sim1*' at maximum deformation.
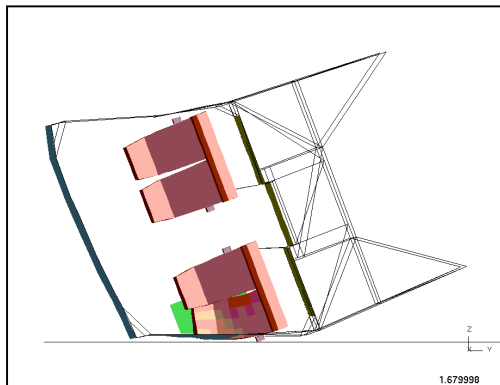
Figure 12. Model '*bay_sim1*' at permanent deformation.

Bay Section Model with Lap-belted Dummies (bay_sim2)

The '*bay_sim2*' model consisted of the following attributes:-

Nodes:	14,495
Beam elements:	357
Shell elements:	11,756
Solid elements:	560
Lumped masses:	58
Spring elements	100
Joint elements:	70
Seatbelt elements	16

The model was calibrated to match the same maximum displacement at the top of the window pillar that was recorded during rollover test 2 (ie. 467mm). In order to achieve the correct displacement, the following parameters were varied:-

- Stiffness and initial slack length of seat belt elements
- Friction coefficient between dummies and seats
- Contact definitions between dummy parts
- Contact definitions between dummies and bay section parts

The following time history graphs for '*bay_sim2*' are shown in the **Appendix**:-

- Figure A6 - displacement time histories at waist level and top of window pillar
- Figure A7 - comparison of FE displacement data with the test data from rollover test 2
- Figure A8 - energy time history graph (kinetic energy and internal energy)

Figures 13 and 14 show the model at the point of maximum deformation and permanent deformation respectively.
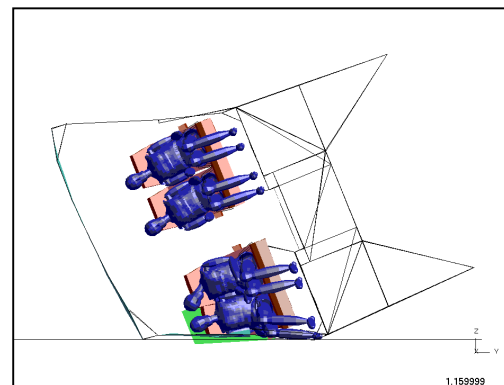
Figure 13. Model '*bay_sim2*' at maximum deformation.
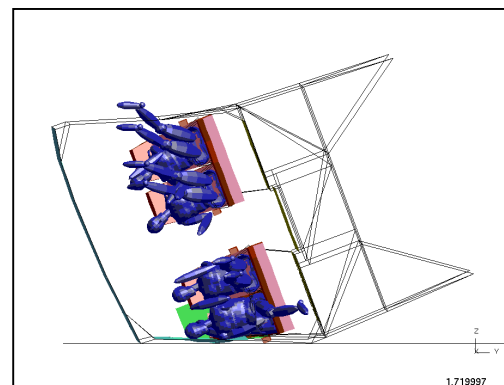
Figure 14. Model '*bay_sim2*' at permanent deformation.

Bay Section Model with 3-point Belted Dummies (bay_sim3)

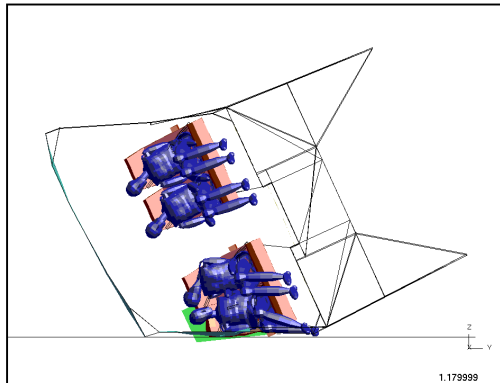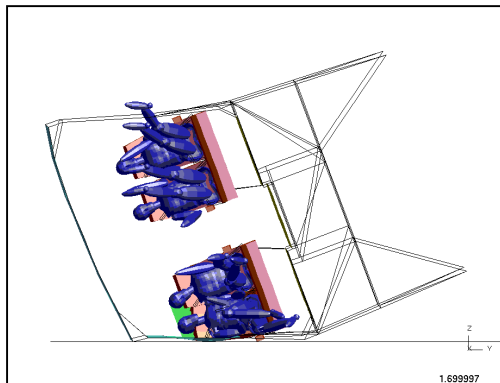The '*bay_sim3*' model consisted of the following attributes:-

Nodes:	14,495
Beam elements:	357
Shell elements:	11,756
Solid elements:	560
Lumped masses:	58
Spring elements	100
Joint elements:	70
Seatbelt elements	28

The '*bay_sim3*' model remained the same as '*bay_sim2*', except for the addition of a shoulder belt for each of the four dummies.

The following time history graphs for '*bay_*sim3' are shown in the **Appendix**:-

- Figure A9 - displacement time histories at waist level and top of window pillar
- Figure A10 - energy time history graph (kinetic energy and internal energy)

Figures 15 and 16 show the model at the point of maximum deformation and permanent deformation respectively.

Figure 15. Model '*bay_sim3*' at maximum deformation.

Figure 16. Model '*bay_sim3*' at permanent deformation.

Bay Section Model with Unrestrained Dummies (bay_sim4)

The '*bay_sim4*' model consisted of the following attributes:-

|	
Nodes:	14,495
Beam elements:	357
Shell elements:	11,756
Solid elements:	560
Lumped masses:	58
Spring elements	100
Joint elements:	70
Seatbelt elements	0

The '*bay_sim4*' model remained the same as '*bay_sim3*', except for the removal of all the seat belt elements and the addition of extra contact definitions.

Each double seat possessed two arm rests (ie. one at each end of the double seat). The pelvis of each dummy was 'wedged' between an arm rest and the other dummy's pelvis, providing contact loads which lightly restrained each dummy into it's seat. Also the outer hand of each dummy (ie. the one close to an arm rest) was fixed to the arm rest to represent the occupant holding on. This restraint was removed once the bay section contacted the ground, in order to represent the occupant's grip being jerked free.

The following time history graphs for '*bay_*sim4' are shown in the **Appendix**:-

- Figure A11 - displacement time histories at waist level and top of window pillar
- Figure A12 - energy time history graph (kinetic energy and internal energy)

Figures 17 and 18 show the model at the point of maximum deformation and permanent deformation respectively.
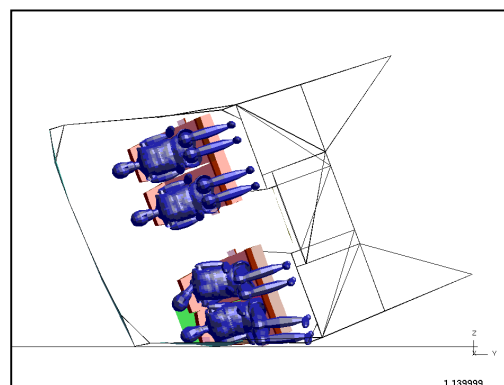
Figure 17. Model '*bay_sim4*' at maximum deformation.
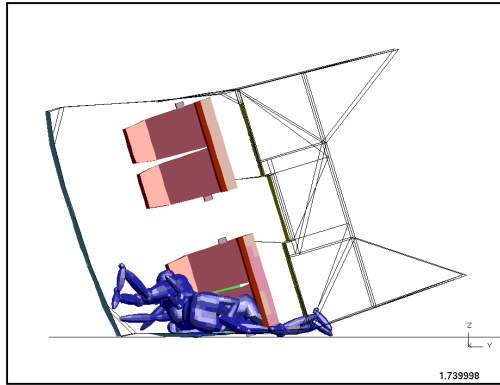
Figure 18. Model *'bay_sim4'* at permanent deformation.

DISCUSSION

Table 1 below summarises the main results from the rollover tests and computer simulations.

Table 1. Summarised results from rollover tests and computer simulations.

OCCUPANT CONFIGURATION	TEST RESULTS		SIMULATION RESULTS						
	Roof max. (mm)	Roof perm. (mm)	Roof max. (mm)	Roof perm. (mm)	Impact KE (kJ)	IE max. (kJ)	IE perm. (kJ)	E* Factor [1]	Occ Mass Factor [2]
None	414	340	415	340	21.1	16.0	11.8	76%	---
4 (Lap-belted)	467	380	467	380	25.9	18.8	13.5	73%	**71%**
4 (3-point belted)	---	---	483	395	26.1	19.1	13.7	73%	**93%**
4 (Unrestrained)	---	---	428	276	25.8	17.1	10.4	66%	**18%**

Table notes:-

1. E* factor = IE max. / Impact KE
2. The occupant mass factor is a measure of the effective mass of the occupants that is coupled to the coach during rollover. This is based on the displacement of the structure and uses the following boundary criteria:-

    • 0% is equivalent to bay section with no dummies (ie. 415mm max. displacement)

    • 100% is equivalent to bay section with four dummies rigidly attached in seats (488mm max. displacement, obtained from additional simulation model not reported)

From the above table it can be seen that for **lap-belted** occupants the effective mass of the occupant coupled to the rollover structure is **71%**.

For the **3-point belt** system, the effective mass of the occupant coupled to the rollover structure is **93%.** The shoulder belt restrains the torso effectively to the seat back allowing only the head, neck and legs to move freely.

The **unrestrained** dummies increased the maximum structural displacement from 415mm to 428mm, representing an occupant mass factor of **18%**. This figure depends significantly on the how the dummies react during the freefall phase of the rollover. During this simulation each pair of dummies were held into their seats by being 'wedged' between the two arm rests. This resulted in the two offside dummies being in mid-air by the time the maximum structural deformation occurs. The 'flying' dummies then contact the bay section as it is recovering it's elastic deformation, having the effect of increasing this recovery and resulting in a relatively low permanent structural displacement of 276mm.

A simple extrapolation of the results above can be made in order to assess the effect of belted passengers on a typical full length coach:-

- A typical coach would possess seven energy absorbing 'rings' which could be loaded with up to 56 passengers (ie. 8 passengers per 'ring')

- The rollover **test** using **lap-belted** dummies showed an increase in the roof corner displacement of two 'rings' by an extra 53mm. Therefore,

  ⇨ 2 dummies per ring   = 53mm

  ⇨ 8 dummies per ring   = 4 x 53 = 212mm

  Therefore, a fully laden coach of 56 **lap-belted** passengers could increase the roof corner displacement by **212mm** toward and beyond the passenger residual space.

- The rollover **simulation** using **3-point belted** dummies showed an increase in the roof corner displacement of two 'rings' by an extra 68mm. Therefore,

  ⇨ 2 dummies per ring   = 68mm

  ⇨ 8 dummies per ring   = 4 x 68 = 272mm

  Therefore, a fully laden coach of 56 **three-point belted** passengers could increase the roof corner displacement by **272mm** toward and beyond the passenger residual space.

CONCLUSIONS

The mass of the occupant that is effectively coupled to the coach structure during the R66 rollover test is:-

- Lap-belted occupants   71%
- 3-point belted occupants   93%
- Unrestrained occupants   18%

REFERENCES

1. UN-ECE Regulation 66, '*Uniform Provisions Concerning the Approval of Large Passenger Vehicles with Regard to the Strength of their Superstructure*'.

2. TransBus International (Plaxton Coach and Bus), Eastfield, Scarborough, North Yorkshire, UK.
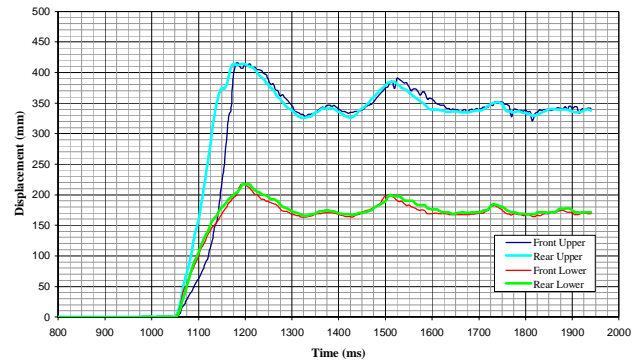
Figure A1. Displacement time history for Rollover Test 1: Bay section, no dummies.
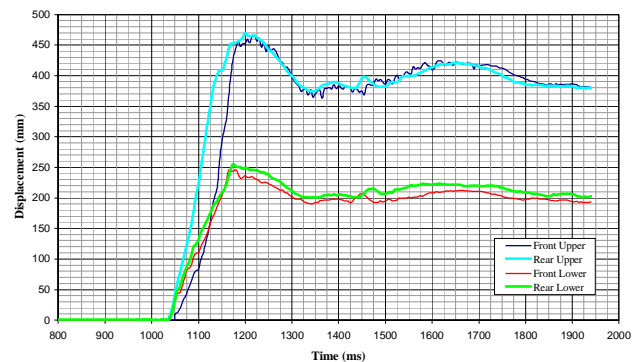

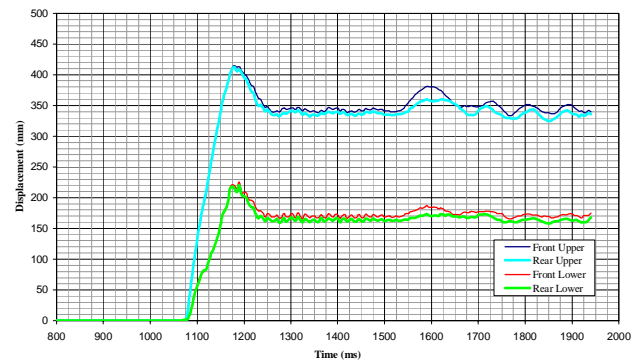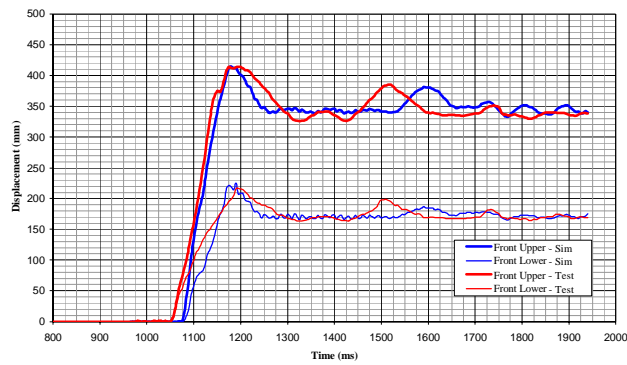**Figure A2. Displacement time history for Rollover Test 2: Bay section, lap-belted dummies.**
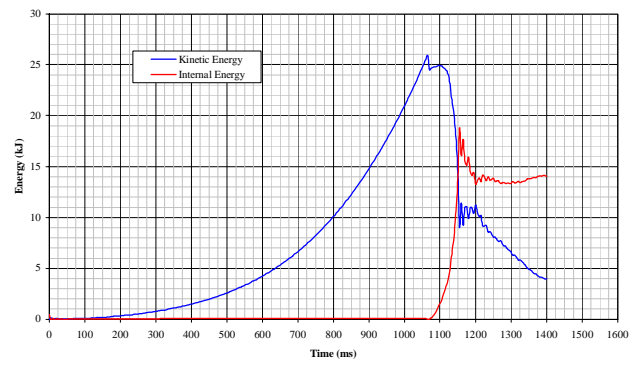

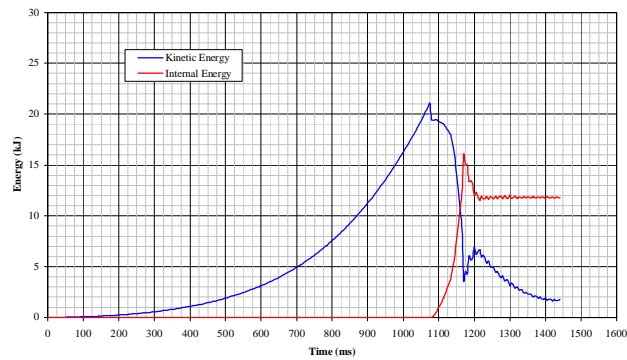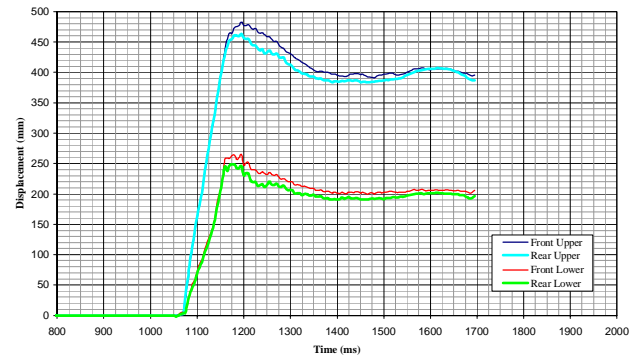**Figure A3. Displacement time history graph for '*bay_sim1*' model: Bay section with no dummies.**

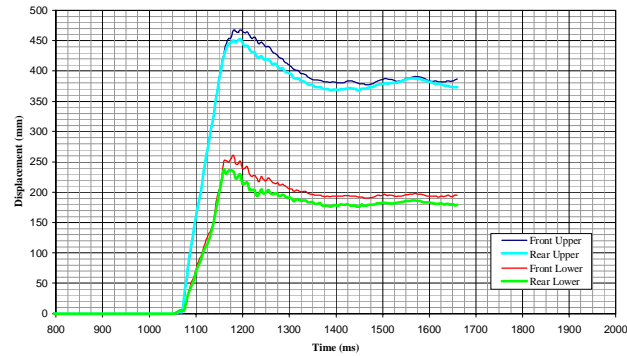**Figure A4. Comparison of FE (blue) and test (red) time history data for 'no dummy' scenario.**
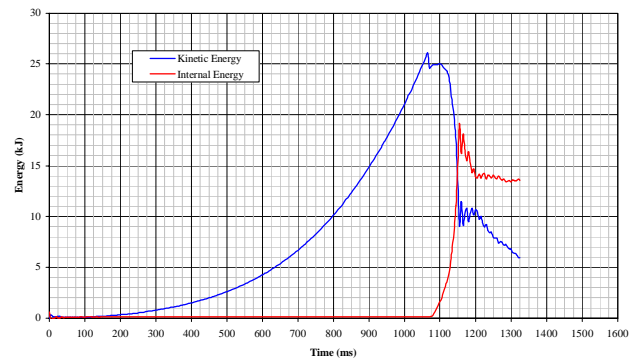

Figure A5. Energy time history for '*bay_sim1*' model: Bay section with no dummies.

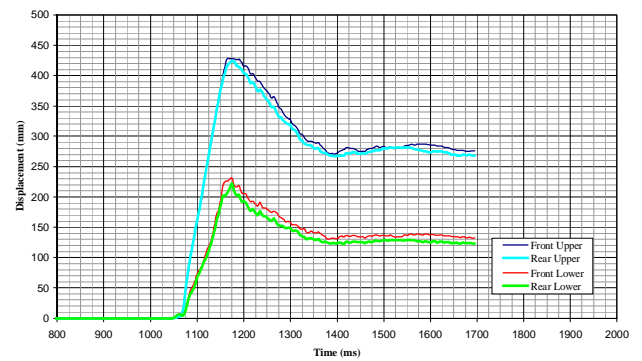**Figure A6. Displacement time history graph for '*bay_sim2*' model: Bay section with lap-belted dummies.**

Figure A7. Comparison of FE (blue) and test (red) time history data for the 'lap-belted dummies' scenario .

Figure A8. Energy time history for '*bay_sim2*' model: Bay section with lap-belted dummies.

Figure A9. Displacement time history graph for '*bay_sim3*' model: Bay section with 3-point belted dummies.
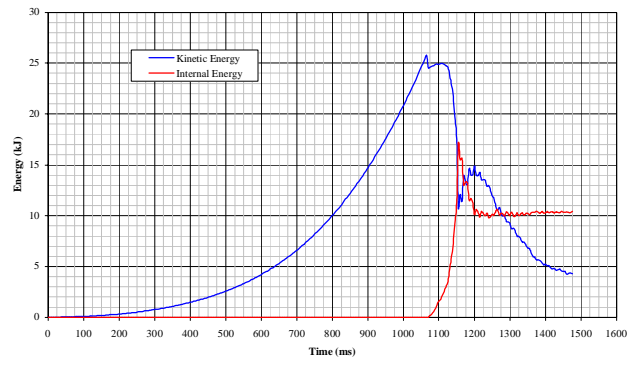

Figure A10. Energy time history for '*bay_sim3*' model: Bay section with 3-point belted dummies.

Figure A11. Displacement time history graph for '*bay_sim4*' model: Bay section with unrestrained dummies.

Figure A12. Energy time history for '*bay_sim4*' model: Bay section with unrestrained dummies.